Catchment Discretization in the Colorado Urban Hydrograph Procedure: A Case Study in the East Toll Gate Creek Watershed, Arapahoe County, Colorado

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Abstract

This technical note presents a case study to show how catchment discretization affects the runoff hydrograph predicted by the Colorado Unit Hydrograph Procedure (CUHP), using the software CUHP 2005 versions 1.2.1c and 1.3.1. A series of hydrologic analyses were performed on the East Toll Gate Creek watershed, Arapahoe County, Colorado. CUHP 2005 was used to generate hydrographs for each catchment or sub-catchment, and the Environmental Protection Agency's Storm Water Management Model (SWMM) was used to route hydrographs between sub-catchments. CUHP 2005 inputs were calculated using the software ArcHydro, using topographic data from the U.S. Geological Survey and from Arapahoe County. To study the effect of catchment discretization, a single-catchment model was compared to subdivided models having 2, 3, 4, 5, and 6 sub-catchments. With 51.4% imperviousness, corresponding to developed conditions, the predicted peak flow for a single-catchment model was 1,741 cfs with CUHP 2005 version 1.2.1c and 1,739 cfs with version 1.3.1. With each subdivision, the predicted peak flow increased. With a maximum of 6 sub-catchments, the predicted peak flow was 2,114 cfs with CUHP 2005 version 1.2.1c and 2,110 cfs with version 1.3.1, in both cases representing a 21% increase over the single-catchment model. With 2.0% imperviousness, corresponding to undeveloped conditions, the effect of catchment discretization was magnified, with a 6 sub-catchment model in CUHP 2005 version 1.2.1c predicting a peak flow more than double that from the single-catchment model. This study demonstrates that catchment discretization affects CUHP 2005 model results, at least in this particular watershed, but with smaller discretization effects in more developed watersheds. Discretization did not affect predicted runoff volume.

Introduction

In watersheds lacking rainfall-runoff measurements, regionally calibrated hydrologic models are used to estimate flows for design of hydraulic structures and identification of flood hazard areas. The Colorado Urban Hydrograph Procedure (CUHP), maintained by the Urban Drainage and Flood Control District (UDFCD) of Denver, Colorado is one such regionally calibrated model (UDFCD 2008a). This model produces unit hydrographs for watersheds in the Denver metropolitan area using the software CUHP 2005. To combine results from separate sub-catchments, UDFCD specifies that routing

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elements be modeled by the Storm Water Management Model (SWMM), maintained by the U.S. Environmental Protection Agency (Rossman 2008).

Catchment discretization has long been recognized as a nontrivial aspect of rainfall-runoff modeling. For comparison, it is useful to consider previous work on the role of catchment discretization in SWMM, which dates back more than a quarter century. When combining sub-catchments into single-catchment models, Zaghloul (1981) and Marsalek (1983) recommend using area-weighted averages for watershed properties and length-weighted averages for channel properties, and then modifying the aggregated hydraulic catchment width, W, such that results from the single-catchment model match those from the subdivided model. Specifically, Marsalek (1983) recommends adjusting the aggregated W such that the time of concentration for the single-catchment model matches the time of concentration for the sub-catchment model plus the transport time in the relevant routing element. This approach is consistent with Bedient et al. (2008), who note that the hydraulic catchment width, W, is essentially a calibration parameter in SWMM. In contrast, CUHP 2005 is a calibrated model, so it contains no adjustable parameters equivalent to the hydraulic catchment width W.

This technical note presents a case study, partially taken from the first author's master report at the University of Colorado Denver (Dankenbring 2008), to show that catchment discretization affects CUHP 2005 model results. Specifically, it will be demonstrated that modeling a particular watershed as a single catchment predicts smaller peak flow compared to modeling the same watershed as 2 sub-catchments connected by a routing element. Similar effects will be demonstrated through further subdivision into up to 6 sub-catchments. This catchment discretization effect will be shown to be more pronounced for undeveloped watersheds than for developed watersheds.

Methods

A series of hydrologic analyses were performed for the East Toll Gate Creek watershed upstream of Gun Club Road, in Sections 7, 18 and 19, Township 5 South, Range 65 West of the 6th Principal Meridian in Arapahoe County, Colorado (Figure 1).

CUHP 2005 versions 1.2.1c and 1.3.1 were used to calculate 5-minute runoff hydrographs for 100 year events using the "rainfall by distribution" option with a one hour depth of 2.67 in (UDFCD 2008b). For each catchment or sub-catchment, CUHP 2005 requires 8 watershed parameters:

1. catchment area A
2. length to centroid L_{ca}
3. catchment length L
4. catchment slope S
5. percent imperviousness
6. pervious retention
7. impervious retention
8. directly connected impervious area (DCIA) level

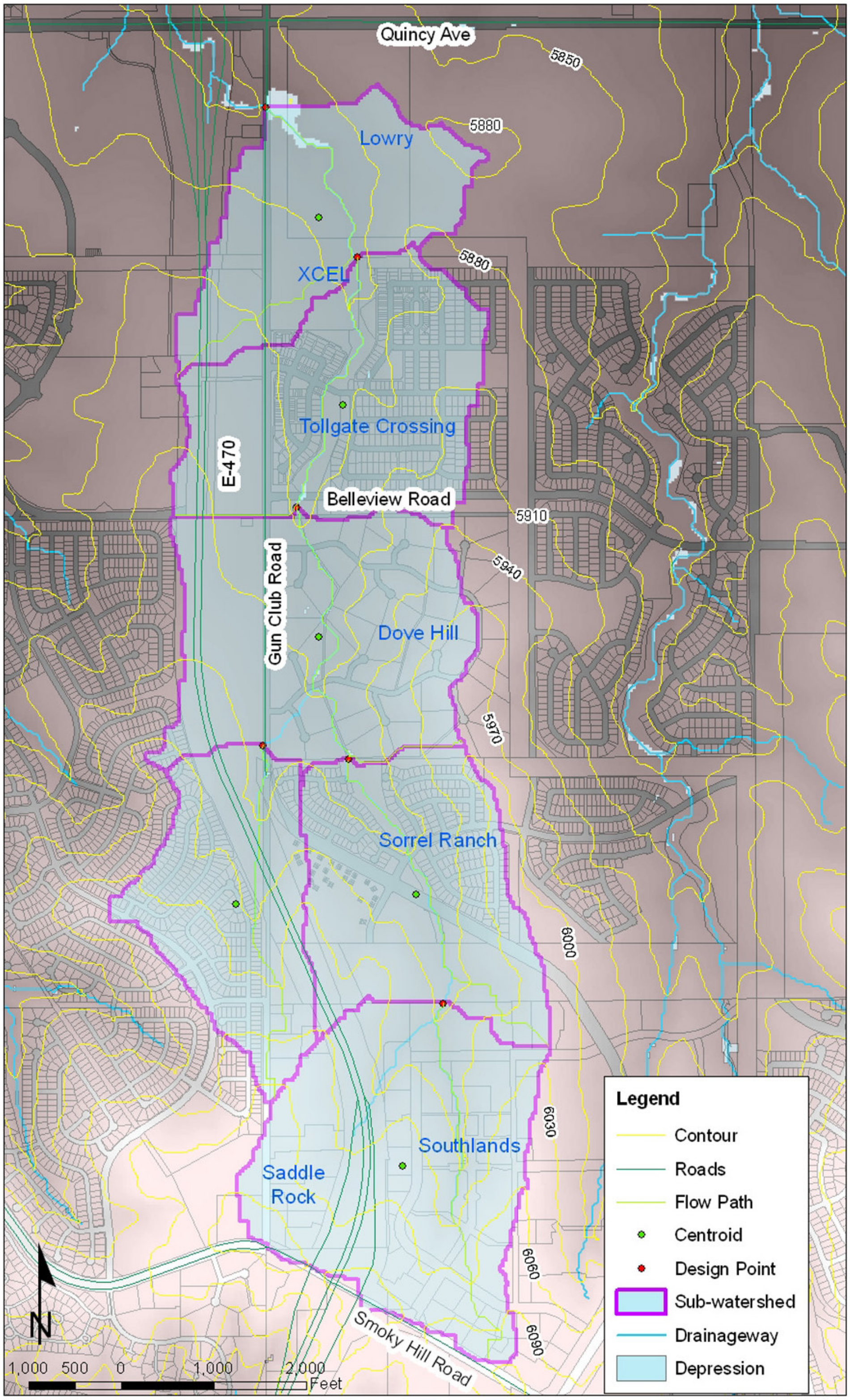

Figure 1: East Toll Gate Creek watershed, Arapahoe County, Colorado.

and the 3 Horton infiltration parameters,

9. initial infiltration rate f_i
10. final infiltration rate f_o
11. decay constant, α.

A, L, L_{ca}, and S were calculated with ArcHydro 1.2, based on a 10 m resolution digital elevation model (DEM) available from the U.S. Geological Survey (USGS). The percent imperviousness was based on Arapahoe County land use data, which was then converted to an average percent imperviousness. The pervious retention, impervious retention, and the DCIA level were assumed to be 0.35 in, 0.1 in, and 1 (unitless), respectively. Horton infiltration parameters were based Natural Resources Conservation Service (NRCS) soil types, determined using NRCS's Soil Survey Geographic (SSURGO) database. The resulting soil types were then converted to Horton parameters following UDFCD specifications (UDFCD 2008b). Horton's equation is

$$f=f_o+(f_i-f_o)e^{-\alpha t}, \tag{1}$$

where f_i is the initial infiltration rate (in/hr), f_o is the final infiltration rate (in/hr), α is the decay coefficient (1/s), and t is time (s).

To evaluate the effect of catchment discretization, the catchment was subdivided into 2, 3, 4, 5, and 6 sub-catchments, and then ArcHydro was used to calculate A, L, L_{ca}, and S for the entire watershed and for each sub-catchment. Results for the single-catchment model and for the model with 6 sub-catchments are provided in Table 1. Corresponding results for 2-5 sub-watersheds are available in Dankenbring (2008). To simplify the analysis, the percent imperviousness and Horton infiltration parameters were assumed to be uniform across all sub-catchments. The constant percent imperviousness was 51.4%, calculated from an area-weighted average of existing developed conditions, and was assumed to be 2.0% for undeveloped conditions. The

Table 1: CUHP 2005 inputs determined from ArcHydro analysis. All areas and slopes fall within UDFCD's (2008b) specified ranges for CUHP 2005 inputs, which are of 90-3,200 acres for area, and 0.005-0.037 ft/ft for slope.

Single Catchment	**Area (ac)**	**Length (mi)**	**L_{ca} (mi)**	**Slope (ft/ft)**
East Toll Gate Creek	930	3.173	1.619	0.0172
6 Sub-Catchments	**Area (ac)**	**Length (mi)**	**L_{ca} (mi)**	**Slope (ft/ft)**
Lowry/XCEL	121	0.910	0.295	0.0169
Tollgate Crossing	165	0.864	0.374	0.0189
Dove Hill	182	0.905	0.325	0.0259
Sorrel Ranch	147	0.851	0.368	0.0231
Saddle Rock/Southlands	200	0.856	0.374	0.0329
West of E-470	115	0.838	0.355	0.0324

constant Horton infiltration parameters were determined from NRCS soil type C, which represented 67% of the soils.

ArcHydro employs several processes for catchment analysis, summarized by ESRI (2007). Some of the major processes completed were manipulating the surface to remove sinks and depressions, delineating sub-catchments, and determining flow paths within each catchment. The next steps included setting batch points for where the sub-catchments are to be delineated and running the sub-catchment analysis. The flow path was then determined for each sub-catchment.

Runoff hydrographs from sub-catchments were routed with EPA's SWMM version 5.0, using the kinematic wave option. For each routing element, SWMM requires 4 inputs:

1. channel length (L_c)
2. channel slope (S_c)
3. Manning's *n*
4. channel cross section.

L_c and S_c were calculated with ArcHydro based on a 10 m DEM from USGS (Table 2). Manning's *n* was determined by a field visit to determine how vegetated the existing channel was. In most areas there was grassy vegetation, with some areas of wetlands in the channel bottom. The corresponding values of Manning's *n* of 0.35 s/m$^{1/3}$ and 0.40 s/m$^{1/3}$, respectively, were then increased by 25% following UDFCD (2008a) specifications (Table 3). The typical cross section (Figure 2) was determined by using a detailed survey of 1 foot contours and field shots of the channel, and was assumed to represent all routing elements.

Results

Under developed conditions (percent imperviousness 51.4%), the single catchment predicted peak flow is 1,741 cfs for CUHP 2005 version 1.2.1c and 1,739 cfs for version 1.3.1. These results are directly from CUHP 2005, since no SWMM routing elements

Table 2: SWMM sub-catchment inputs determined from ArcHydro analysis.

Upstream Point	**Downstream Point**	**Upstream Elev. (ft)**	**Downstream Elev. (ft)**	**L_c (ft)**	**S_c (ft/ft)**
Southlands	South Dove Hill	5,962	5,922	3,282	0.012
South Dove Hill	Crestline	5,922	5,906	1,014	0.016
South Gun Club Road	Crestline	5,923	5,906	930	0.018
Crestline	Belleview Road	5,906	5,873	2,420	0.014
Belleview Road	North Tollgate Crossing	5,873	5,839	3,195	0.010
North Tollgate Crossing	Gun Club Road	5,839	5,823	2,323	0.0069

Table 3: SWMM channel inputs determined from ArcHydro analysis.

Station (ft)	Elevation (ft)	Manning's *n* (s/m$^{1/3}$)	Corrected Manning's *n* (s/m$^{1/3}$)
0	100	0.040	0.050
100	90	0.040	0.050
230	86.7	0.040	0.050
270	86.4	0.040	0.050
310	84.8	0.035	0.044
314	83.7	0.035	0.044
322	83.6	0.035	0.044
326	83.7	0.035	0.044
330	85.1	0.035	0.044
432	90.1	0.040	0.050
532	100	0.040	0.050

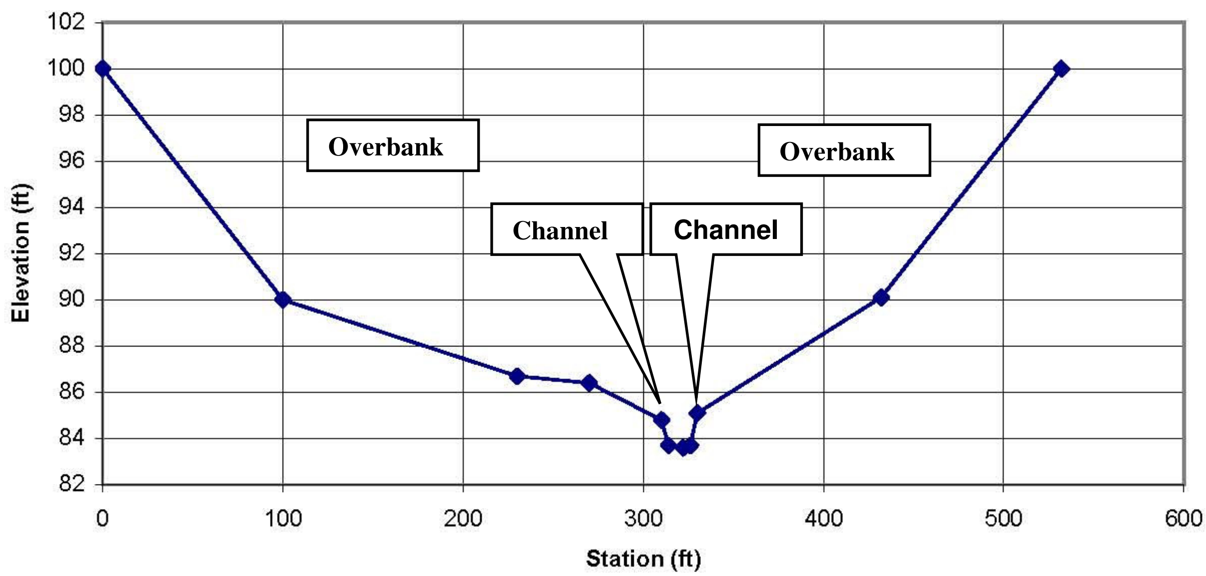

Figure 2: Typical channel section used for routing by SWMM.

are required when modeling the entire watershed as a single catchment. When subdivided into 6 sub-catchments, the peak flow is 2,114 cfs for CUHP 2005 version 1.2.1c and 2,110 cfs for version 1.3.1. These results, plus the corresponding results for 2-5 sub-catchments are provided in Table 4 and Figures 3 and 4. For both versions of CUHP 2005, the increase in predicted peak flow from the single-catchment model to the 6 sub-catchment model is 21%. These results demonstrate that successive catchment discretization in this watershed causes increasing predicted peak flows.

For comparison, the effect of catchment discretization was also analyzed for undeveloped conditions (percent imperviousness 2.0%). This analysis was performed in CUHP 2005 version 1.2.1c, which was the current version in early 2008 during the first author's graduate research at the University of Colorado Denver. For the single-catchment model, the predicted peak flow is 573 cfs. When subdivided into 6 sub-catchments, the peak flow is 1,158 cfs. These results, plus the corresponding results for 2-5 sub-catchments are provided in Table 4 and Figure 5. For undeveloped conditions, the predicted peak flow approximately doubles between the single-watershed and 6 sub-catchment models. These results indicate more pronounced effects of catchment discretization in this watershed for smaller percent imperviousness.

Catchment discretization had no effect on predicted runoff volumes, which varied from 162-165 acre-feet in both versions of CUHP 2005 for developed conditions, and from 127-129 acre-feet for undeveloped conditions.

Discussion

To put these results in context, it may be helpful to consider the previous work by Guo and Urbonas (2008), who also studied catchment discretization effects in CUHP 2005. They compared a single-catchment model with various subdivided models for a hypothetical rectangular watershed, both for CUHP 2005 *now* and CUHP 2005 *revised*. The corresponding version numbers were not specified, but since their report is dated 8/4/2008, we presume that *now* refers to version 1.2.1c, released 2/20/2008, or version 1.3.1, released 8/11/2008 (UDFCD 2008a), while *revised* refers to an unreleased version of CUHP 2005 (James Guo, personal communication, 10/5/2009).

Table 4: Effect of catchment discretization on predicted peak flows, where *developed* is 51.4% imperviousness, and *undeveloped* is 2.0% imperviousness.

condition	**Developed**		**Developed**		**Undeveloped**	
CUHP 2005	**version 1.2.1c**		**version 1.3.1**		**version 1.2.1c**	
discretization	**Q_p (cfs)**	**V (ac-ft)**	**Q_p (cfs)**	**V (ac-ft)**	**Q_p (cfs)**	**V (ac-ft)**
single catchment	1,741	162	1,739	162	573	127
2 sub-catchments	1,766	164	1,764	164	749	128
3 sub-catchments	1,875	164	1,872	164	871	129
4 sub-catchments	1,974	165	1,969	165	999	129
5 sub-catchments	2,057	165	2,038	165	1,082	129
6 sub-catchments	2,114	162	2,110	162	1,158	128

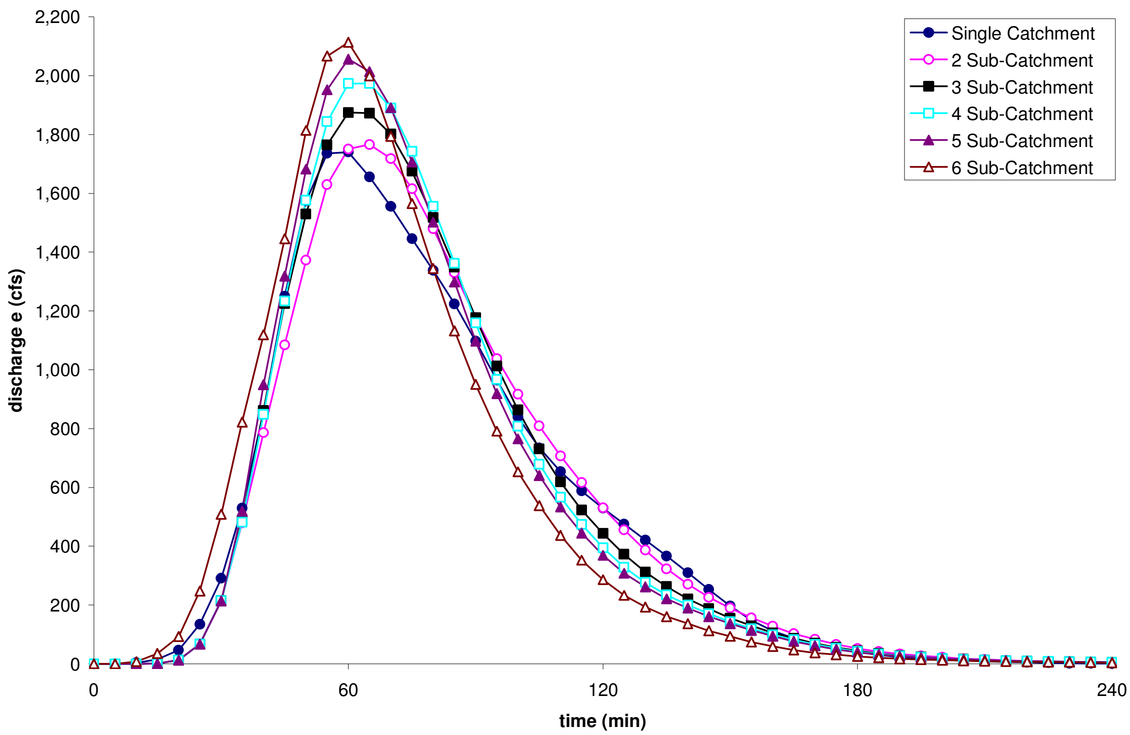

Figure 3: Effect of catchment discretization in CUHP 2005 version 1.2.1c with 51.4% imperiousness (developed case).

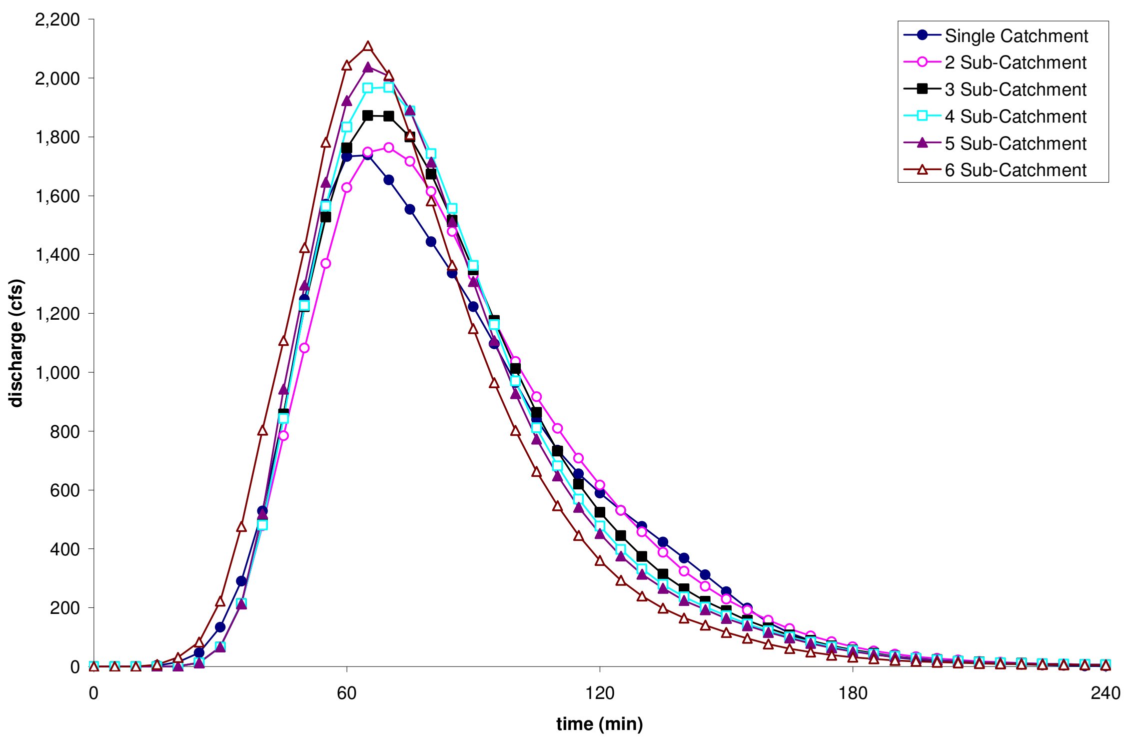

Figure 4: Effect of catchment discretization in CUHP 2005 version 1.3.1 with 51.4% imperiousness (developed case).

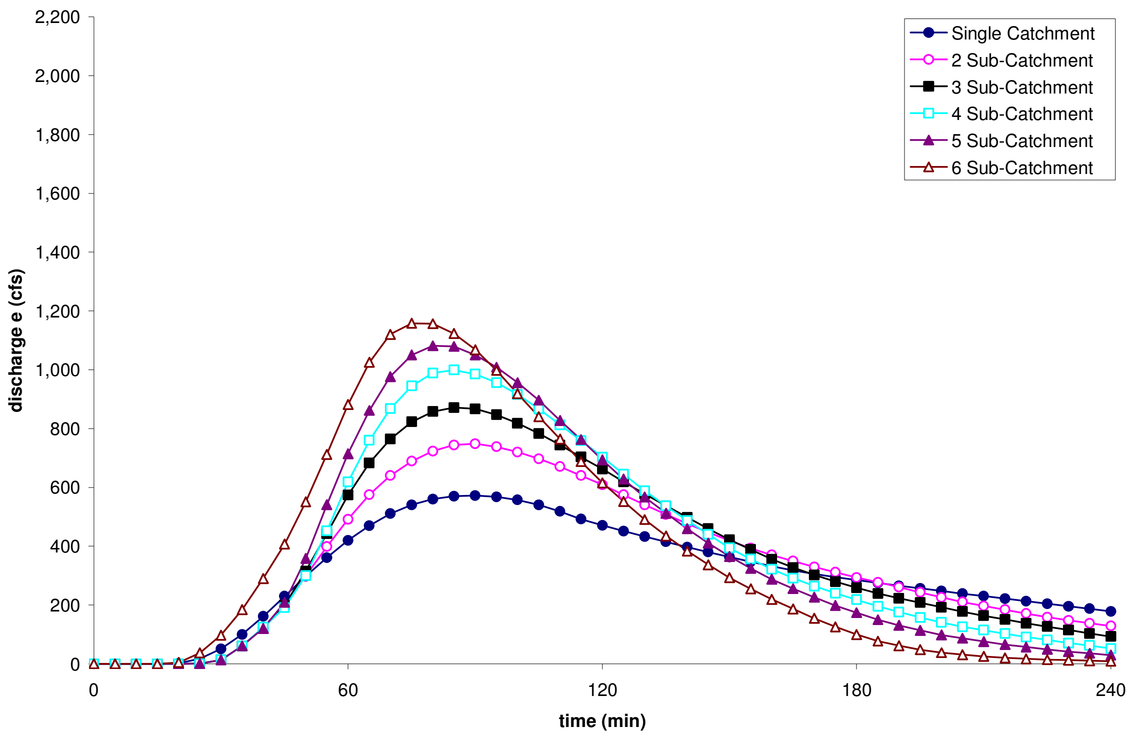

Figure 5: Effect of catchment discretization in CUHP 2005 version 1.2.1c with 2% imperiousness (undeveloped case).

With an assumed imperviousness of 40%, Guo and Urbonas (2008) report that applying CUHP 2005 *now* to a 6 sub-catchment model predicts a peak flow 32% higher compared to a single-catchment model. This finding is consistent with the results of the present study (Table 5 and Figure 6). The correlation in Figure 6 is notable, because it demonstrates an apparently consistent pattern between the East Toll Gate Creek watershed analyzed in this study and the hypothetical watershed analyzed by Guo and Urbonas. However, it is not currently possible to assign a confidence interval to the slope or intercept on the plotted line of best fit, owing to the small number of available data. In contrast, when using CUHP 2005 *revised*, Guo and Urbonas report that the 6 sub-catchment model is only 6% higher than the single-catchment model, suggesting that discretization effects may be less pronounced in future versions of CUHP 2005.

Table 5: Comparison of the present study with Guo and Urbonas (2008). Q_1 is the peak flow from a single-catchment model, while Q_6 is from a 6 sub-catchment model.

study	version	imperviousness	Q_1 [cfs]	Q_6 [cfs]	increase
this study	1.2.1c	2.0%	573	1158	102%
Guo and Urbonas (2008)	now	40%	718	947	32%
this study	1.2.1c	51.4%	1741	2114	21%

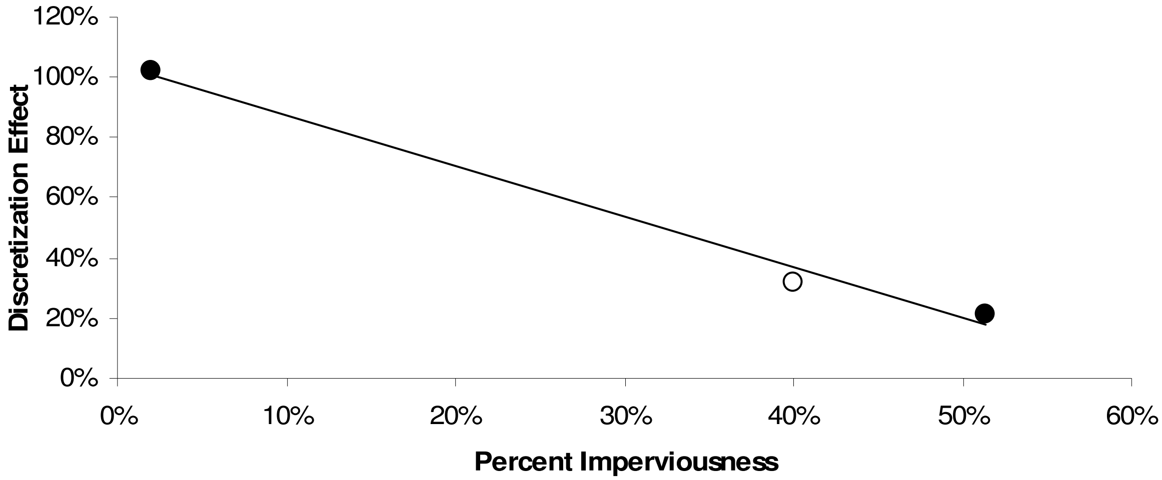

Figure 6: Correlation between the percent imperviousness and the discretization effect, expressed as the percent increase from Q_1 to Q_6 from Table 5, for CUHP 2005 version 1.2.1c (this study - black dots) and CUHP 2005 *now* (Guo and Urbonas - white dot). The line was fitted by least squares.

In a broad sense, catchment discretization—the choice of whether to represent a given watershed as a single catchment without routing elements or as a collection of sub-catchments connected by routing elements—is essentially a choice between conceptual models. For the case of East Toll Gate Creek watershed, this technical note has demonstrated that using the same methodology to select the CUHP 2005 input parameters, irrespective of the conceptual model selected, leads to inconsistent model predictions. This is a special case of the well-known fact that hydrologic models depend on the conceptual model selected (Anderson 1992, Fitts 2002).

In an ideal world, hydrologic models would be based on measurable watershed characteristics, would not require calibration, and would be independent of catchment discretization. In practice, hydrologic models do require calibration, due to the difficulty in representing the full complexity the rainfall-runoff process in a finite set of model parameters. SWMM contains the calibration parameter *W*, which makes it flexible, but difficult to apply in ungaged watershed. By adjusting *W*, it is possible to compensate for catchment discretization effects in SWMM. In contrast, CUHP 2005 contains no equivalent calibration parameter, which makes it straightforward to apply in the Denver metropolitan area, but makes it dependent on catchment discretization. The present study confirms Guo and Urbonas's (2008) observation that "the level of watershed discretization can cause an artificial increase in the peak runoff predicted at the outfall point. Often the smaller the subareas, the higher the cumulative peak runoff is at the downstream limits."

Conclusions

1. Runoff predicted by CUHP 2005 versions 1.2.1c and 1.3.1 depends on catchment discretization. Using more sub-catchments increases the predicted peak flow.
2. The effect of catchment discretization is less pronounced in developed watersheds, where CUHP 2005 is more likely to be applied in practice.
3. Catchment discretization has no effect on the predicted runoff volume.

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